Characterization of Saltwater Intrusion in South Florida

Using Electromagnetic Geophysical Methods

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Abstract

Airborne, ground, and borehole electromagnetic measurements have been used to characterize saltwater intrusion in the Everglades and surrounding areas of south Florida. This area is the subject of intensive study as environmental restoration activities are planned and progress. The airborne electromagnetic data are used to develop detailed resistivity models of the subsurface, which show the extent of saltwater intrusion. The influences of natural conditions, as well as human activity, on the patterns of saltwater intrusion are seen with greater clarity in the airborne data than is possible from sampling-well data alone. By combining the widely scattered well information and geophysical logs, a relationship that allows conversion of the resistivity model into estimates of water quality expressed as specific conductance and chloride content is derived. This information is beneficial to the development of a regional ground-water flow model that incorporates solute transport.

Keywords: saltwater intrusion, geophysics, electromagnetics, hydrologic properties, Everglades

Introduction

Saltwater intrusion in south Florida has been studied since the 1950s (Sonenshein, 1997), and its history has been well documented in parts of south Florida for over 100 years (Parker et al., 1955; Leach et al., 1972; Klein and Waller, 1985). Traditionally saltwater intrusion has been studied by means of observation wells to access water quality and levels. While this approach gives very detailed information at a specific location, it can be very expensive due to the cost of drilling and well installation. More problematic is the fact that wells are often widely spaced. In the case of the Florida Everglades well placement is restricted by the limited road network.

Historically the primary focus of salt-water intrusion studies in south Florida has been the evaluation and protection of ground-water resources, which are the principal source of drinking water. Over the past decade environmental concerns related to restoration of the Florida Everglades have become equally important as the connection between the environment and the economy has been recognized. The current restoration activity is a very large and complex project. Resource managers are always looking for better modeling and forecasting tools to assist them as they develop, execute, and

monitor restoration activities. Electromagnetic geophysical techniques are one means of cost effectively improving hydrologic property estimates for ground-water flow models.

The use of borehole, surface, and airborne geophysical techniques to map saltwater intrusion has become more common (Sonenshein, 1997; Fitterman and Deszcz-Pan, 1998, 2002; Chen, 1999; Hittle, 1999; Albouy et al., 2001; Schmerge, 2001). These techniques provide information on subsurface electrical resistivity variations, which can be related to changes of geology and water quality. In this paper we describe the use of electromagnetic geophysical techniques to estimate water quality on a regional scale commensurate with hydrologic modeling activity.

Hydrology of Study Area

The area of interest for this study is composed of the coastal regions of south Florida stretching over three counties: Collier, Monroe, and Miami-Dade. It encompasses large parts of Everglades National Park and Big Cypress National Preserve (see Figure 1). The hydrologic framework of south Florida has been studied by a number of authors as summarized below.
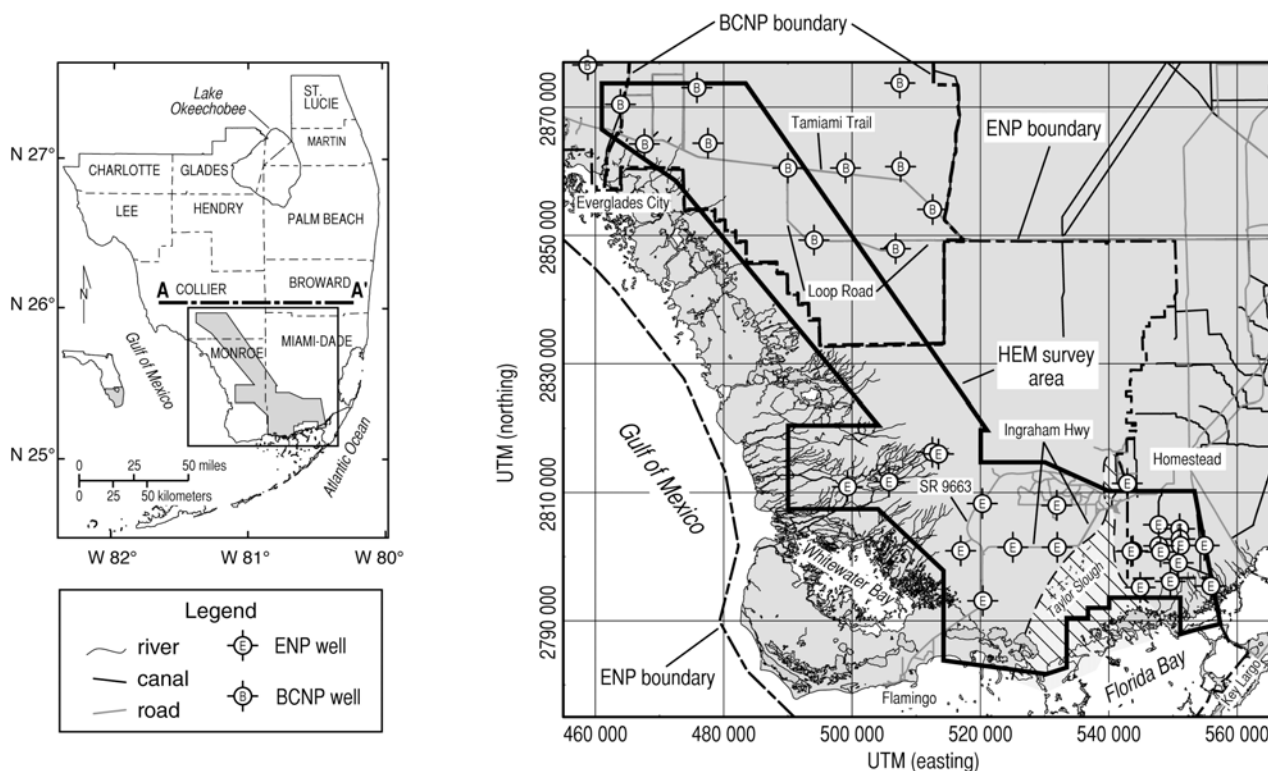

Figure 1 Location map of the Everglades-Big Cypress study area showing wells and helicopter electromagnetic survey boundary. The small index map shows the study location in south Florida and the location of cross section A-A' shown in Figure 2

Fish and Stewart (1991) described the hydrostratigraphy of Miami-Dade County, which encompasses the eastern half of the study area. Reese and Cunningham (2000) present a cross section of the surficial aquifer system (Figure 2) that is located just north of our study area. The surficial aquifer system is composed of four units (see Figure 2). From the surface downward these are: 1) the Biscayne aquifer, composed of limestones and quartz sands; 2) the upper semi-confining unit, composed of quartz sand, sandstone, and mudstone; 3) the Gray limestone aquifer, a pelecypod, lime rudstone and float

stone, pelecypod-rich quartz sand, and moldic quartz sandstone; and 4) the lower semi-confining unit, a moldic pelecypod-rich quartz sand or sandstone. The total thickness of the surficial aquifer system ranges from 55 to 75 m (180-240 ft).
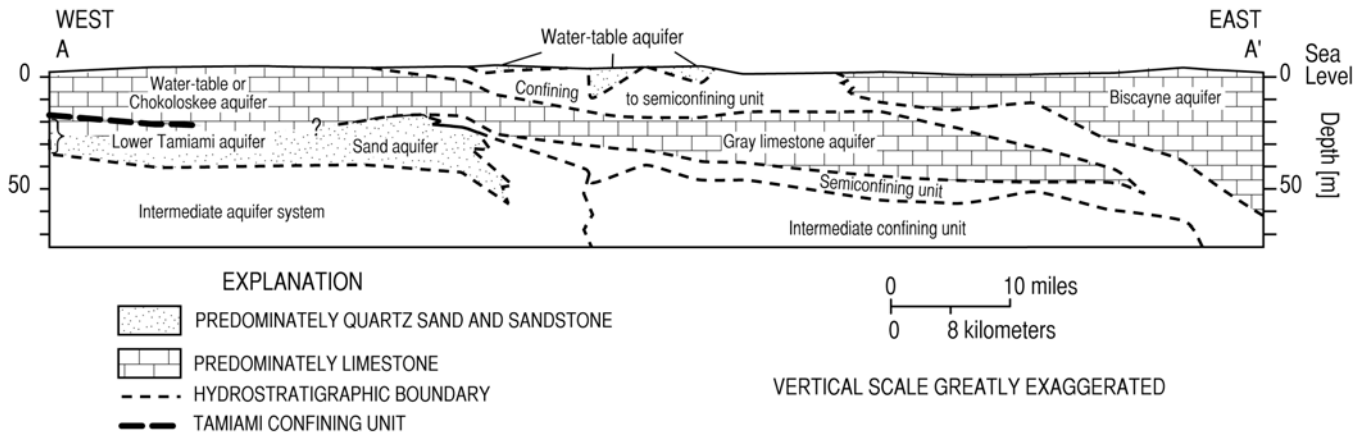

Figure 2 Generalized hydrostratigraphy north of study area (modified from Reese and Cunningham, 2000). Approximate location of cross section is shown in Figure 1.

The Biscayne aquifer is the principal aquifer in eastern Miami-Dade and Broward Counties. Composed of several Pleistocene, Pliocene, and late Miocene age sedimentary units, the Biscayne aquifer is defined on the basis of being a highly permeable zone of at least 3 m (10 ft) thickness and horizontal hydraulic conductivities of 3.5 mm/s (1000 ft/day) or more (Fish and Stewart, 1991). Hydraulic conductivities in excess of 3.5 cm/s (10 000 ft/day) are not uncommon for this aquifer owing to the well developed secondary porosity.

Below the Biscayne aquifer the gray limestone aquifer is found in the western part of Miami-Dade and Broward Counties and Collier and Monroe Counties (Reese and Cunningham, 2000). Reese and Cunningham define the gray limestone aquifer as limestone, sandstone, and quartz sand and sandstone adjacent to the limestone beds with hydraulic conductivity of greater than 0.35 mm/s (100 ft/day) and more than 3 m (10 ft) thick. The Biscayne and gray limestone aquifers can grade into one another. The gray limestone is shallower in the western portion of the area due to the eastward regional dip (Figure 2). Moving further west into much of Monroe County and south-central and western Collier County, the gray limestone becomes the water-table aquifer and is referred to as the Chokoloskee aquifer (Reese and Cunningham, 2000).

Effect of Water Quality on Electrical Properties

The electrical properties of geologic materials have been extensively studied for petroleum exploration applications (Archie, 1942; Waxman and Smits, 1968; Hearst et al., 2000); these methods are directly applicable to ground-water studies (Jorgensen, 1991). The electrical conductivity of water saturated rocks is controlled by the amount of connected pore space, the conductivity of the water in the pore space, and the presence of clay minerals. For fully saturated rocks with no clay minerals present and high conductivity pore fluid, the governing equation is straight forward:

$$\sigma/\sigma_0 = \frac{1}{F} , \qquad (1)$$

where σ is the formation conductivity, σ_0 is the conductivity of the pore fluid, and F is the formation factor. The formation factor is based upon an empirical correlation between σ and σ_0 for a particular geologic formation. This correlation can be established from induction logs and pore water conductivity measurements in boreholes or from measurements of electrical conductivity of core samples saturated with fluids of known conductivity. Equation (1) can be rewritten in terms of formation resistivity (ρ) and pore fluid resistivity (ρ_0) as

$$\rho/\rho_0 = F, \tag{2}$$

where the resistivities are the reciprocal of the corresponding conductivities. The fluid conductivity and resistivity are related to the specific conductance (SC or EC) through the relationship

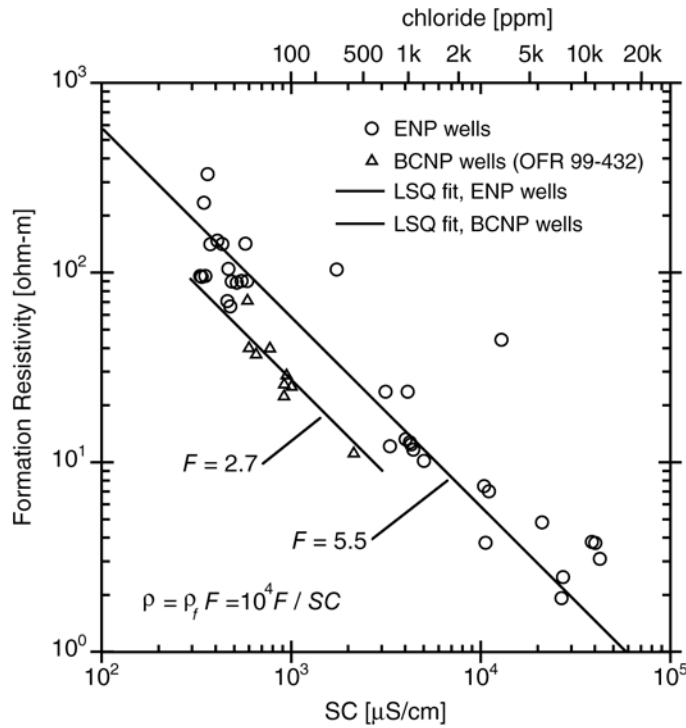$$\sigma_0[S/m] = 1/\rho_0[\text{ohm-m}] = \frac{SC[\mu S/cm]}{10000}. \tag{3}$$

Figure 3 Correlation of formation resistivity and pore water specific conductance (SC) from wells in the study area. The solid lines are least squares fits to the data. The chloride concentration scale is based on an empirical relationship valid for surface water in south Florida.

Data from wells in two regions are shown in Figure 3. (See Figure 1 for well locations.) The first set of wells was drilled for this study in Everglades National Park (ENP) and for an earlier study (Fish and Stewart, 1991), and the second set of wells is from a hydrologic study of the gray limestone near Big Cypress National Preserve (BCNP) (Edwards et al., 1998; Weedman et al., 1999; Reese and Cunningham, 2000). Plotted on logarithmic coordinates are formation resistivity measured in boreholes with an induction logging tool against water specific conductance measured in the borehole or from pumped samples. The induction logs were averaged over the screened interval of the wells, typically 3 m (10 ft).

The ENP (eastern) wells have a formation factor of about 5.5, whereas the BCNP (western) wells have a formation factor of 2.7, a value which is rather low. The difference between the two sets of wells reflects the difference in physical properties moving from the Biscayne aquifer in the east into the gray limestone aquifer in the west. The formation factors can be used to estimate the pore-water specific conductance from formation resistivities determined by geophysical measurements using equations (2) and (3) .

Electromagnetic Measurement of Electrical Properties

There are a wide range of electromagnetic geophysical techniques that have been developed to measure the spatial variation of electrical resistivity in the subsurface (Nabighian, 1988, 1991). In general, these techniques make use of a time-varying, primary magnetic field source called the transmitter, usually consisting of one or more loops of wire through which a time varying current is passed, to induce electrical currents in the Earth. The magnitude of the induced currents depends upon the ability of the ground to conduct electricity and is reflected in the physical property called electrical conductivity. The time-varying induced currents produce a secondary magnetic field that is sensed with a receiver coil. Analysis of the voltage induced in the receiver coil by the magnetic fields can be used to estimate the conductivity of the ground.

Electromagnetic methods can be divided into two large classes. The first, called frequency-domain measurements, make use of a sinusoidally varying current in the transmitter. The secondary magnetic field produced by the induced currents is measured in the presence of the primary magnetic field. There is typically a phase shift between the primary and secondary fields that allows them to be separated for analysis. By varying the frequency of the transmitter current the depth of investigation can be changed with lower frequencies penetrating deeper into the ground. The second class of electromagnetic geophysical measurements are called time-domain or transient methods. With these measurements, the transmitter current is usually held constant for some length of time and then abruptly turned off. The rapid decrease in current and the accompanying collapse of the associated magnetic field induces current flow in the ground. A receiver coil measures the secondary magnetic field produced by this decaying current system in the ground. The measurement is made while the primary magnetic field is absent. In principle, time-domain and frequency-domain measurements should be equivalent, however, the way noise affects the two types of measurements is quite different, leading to advantages for each method (Kaufman and Keller, 1983).

While electromagnetic methods were originally developed for mineral exploration, they have been widely used over the past 20 years for ground-water investigations. Details can be found in a number of publications (Stewart, 1982; Stewart and Gay, 1986; Fitterman and Stewart, 1986; Fitterman, 1987; McNeill, 1990; Fitterman and Labson, 2005). In the work presented here we have used three electromagnetic geophysical techniques: 1) helicopter electromagnetic (HEM) surveying, time-domain electromagnetic (TEM) sounding, and borehole induction logging. The HEM and borehole techniques are frequency-domain methods, while TEM sounding is a time-domain method.

HEM surveying is done using electromagnetic transmitter and receiver coils that are housed in a 10-m long instrument assembly called a bird. The bird is slung below the helicopter on a 30-m long cable and it is flown at a nominal altitude of 30 m. The survey area is covered with flight lines oriented at N50°E and spaced 400 m apart. A measurement is made every second with spacing on the order of 4 to 15 m along flight lines. The birds commonly make measurements at five or more frequencies. Data are used to estimate layered earth models at each measurement point. The resulting conductivity-depth

functions probe to depths varying from 15 to 80 m depending upon the average conductivity value. In conductive regions the depth of exploration is shallower than in resistive (less conductive) regions. HEM data serve as our primary source of subsurface information because of the high sampling density.

Transient soundings were used to obtain an independent estimate of conductivity-depth variation, as well as providing a means of calibrating the HEM instrumentation (Deszcz-Pan et al. 1998). Soundings were made using a central induction array where the 40-m by 40-m transmitter loop surrounds the receiver coil. Depth of exploration varies from 40 to 100 m (Fitterman et al., 1999). Inversion methods were used to convert the apparent resistivity-time data into interpreted resistivity-depth models.

The last electromagnetic method used is induction logging. This is a frequency-domain method that uses a small receiver and transmitter coil housed inside a non-conducting probe that is lowered down a PVC-cased borehole (Hearst et al., 2000). The recorded secondary field is converted to conductivity of the material surrounding the borehole and is measured continuously as the probe moves through the borehole. The induction tool senses about a meter into the surrounding formation. The induction logs were used to establish a relationship between the formation conductivity and the specific conductance (SC) of the pore water. Knowing this relationship and how SC is related to chloride content, we can estimate water quality from the HEM-derived conductivity models

The contrast between the sampling of the HEM and borehole data should be pointed out. Induction logs, as is true for all borehole geophysical techniques, give very detailed information about how a physical property varies with depth in the vicinity of a well. The downside of borehole measurements is that they are only sensitive to material close to the well. Thus, if there were a change of geologic or hydrologic properties a few meters from the borehole, it would not be detected. Contrast this to the HEM data were there is a measurement point every 10 meters along flight lines. While the footprint of the HEM measurement is roughly a 110-m by 110-m patch of ground (Kovach et al., 1995), a size that is comparable to the dimension of hydrologic model cells, it is not likely to miss features because of the nearly continuous data coverage. The vertical resolution of the HEM data are much lower than the vertical resolution of the well logs. So we have a trade off between a few widely spaced high-resolution datum and finely spaced data with reduced vertical resolution. Each in their own way are valuable, and combined they enhance the value of each other.

Description of Helicopter Electromagnetic Results

We display the HEM data as maps of interpreted formation resistivity at a selected depth. Three depth-slice maps for 10, 20, and 40 meters depth are shown in Figures 4 through 6. The discussion below refers to features marked on these maps.

The general pattern seen on the depth-slice maps is a low resistivity zone (<10 ohm-m) near the coast which transitions into a high resistivity region (>50 ohm-m) in the landward direction. This transition is interpreted as being due to a change in formation water from saltwater to freshwater. Near Taylor Slough (see Feature 1 in Figure 4) the transition is fairly abrupt, occurring over a distance of 500 m. Moving parallel the transition, the distance landward of the transition does not vary greatly, i.e. the boundary has a smooth appearance. Taylor Slough in the vicinity of the freshwater-saltwater transition (FWSWT) has no streams flowing into Florida Bay; water flow is overland. In other regions, such as the western part of the ENP survey (Feature 2) or the Big Cypress survey (Feature 3), the FWSWT is wider and more irregular than in Taylor Slough. The many tidal rivers and streams that course deeply inland from the Gulf of Mexico strongly influence the location of the FWSWT because their presence lowers
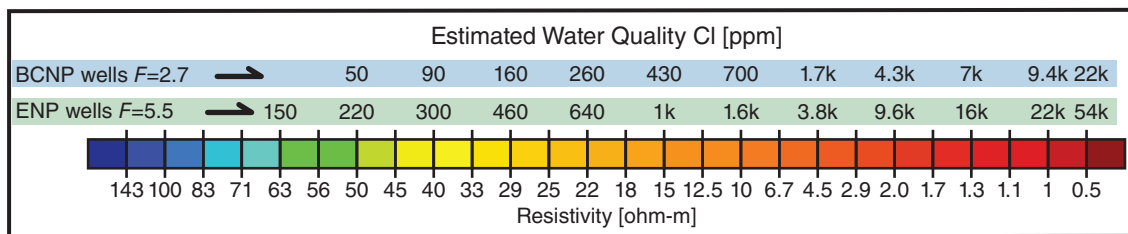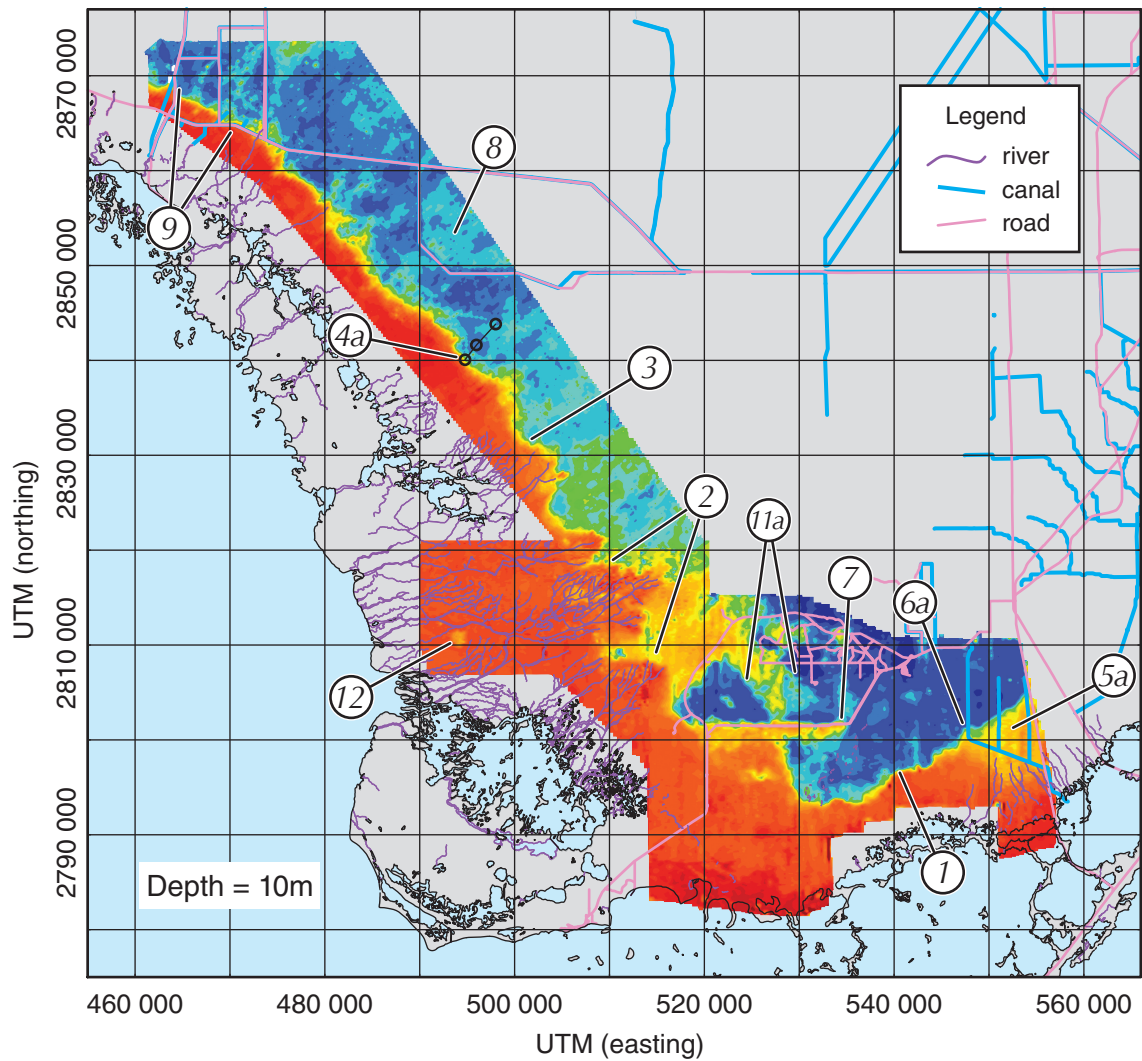
Figure 4 Resistivity depth-slice map at 10m. The color bar is also valid for Figures 5 and 6. Circled numbers designate features that are discussed in the text.
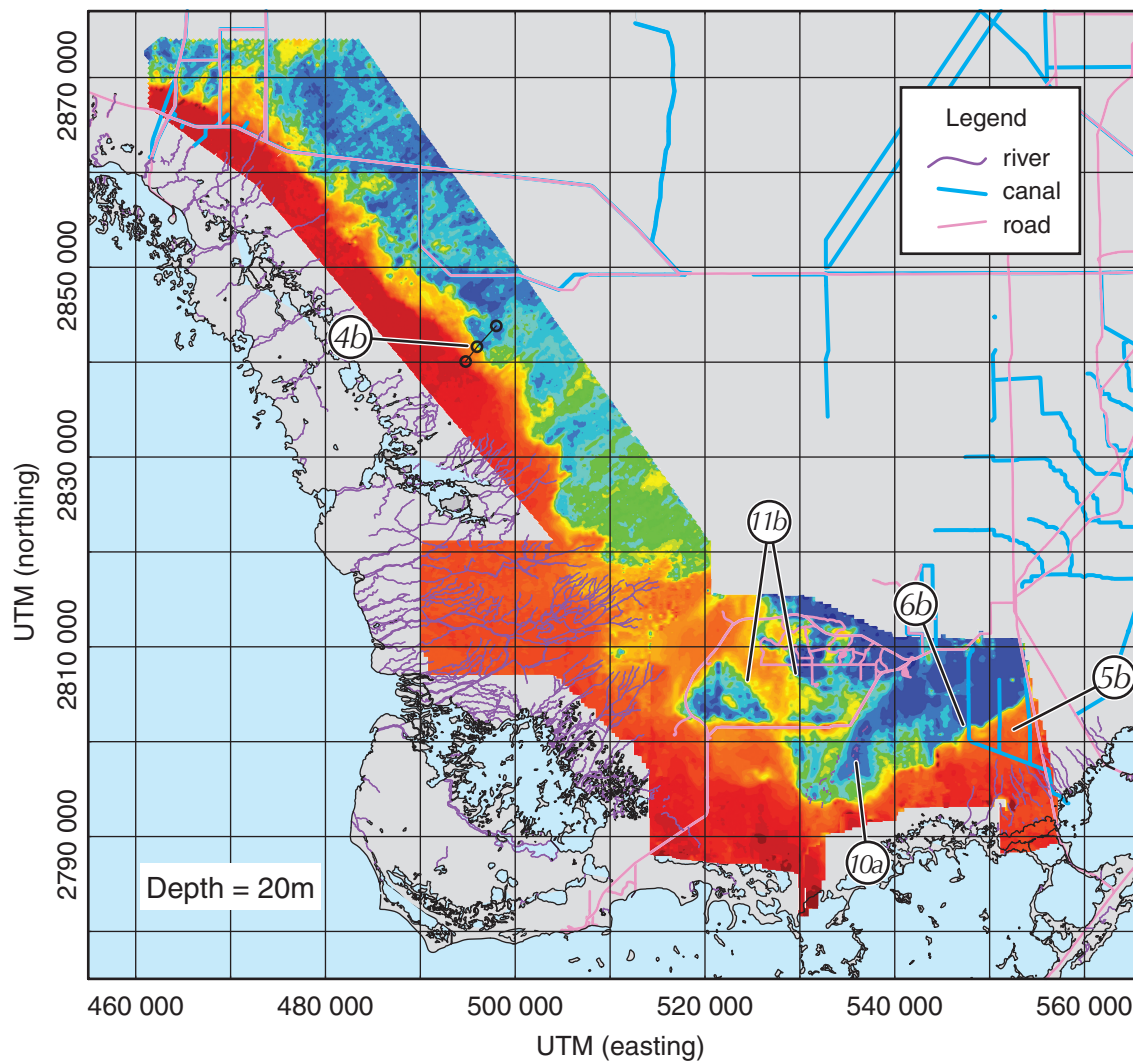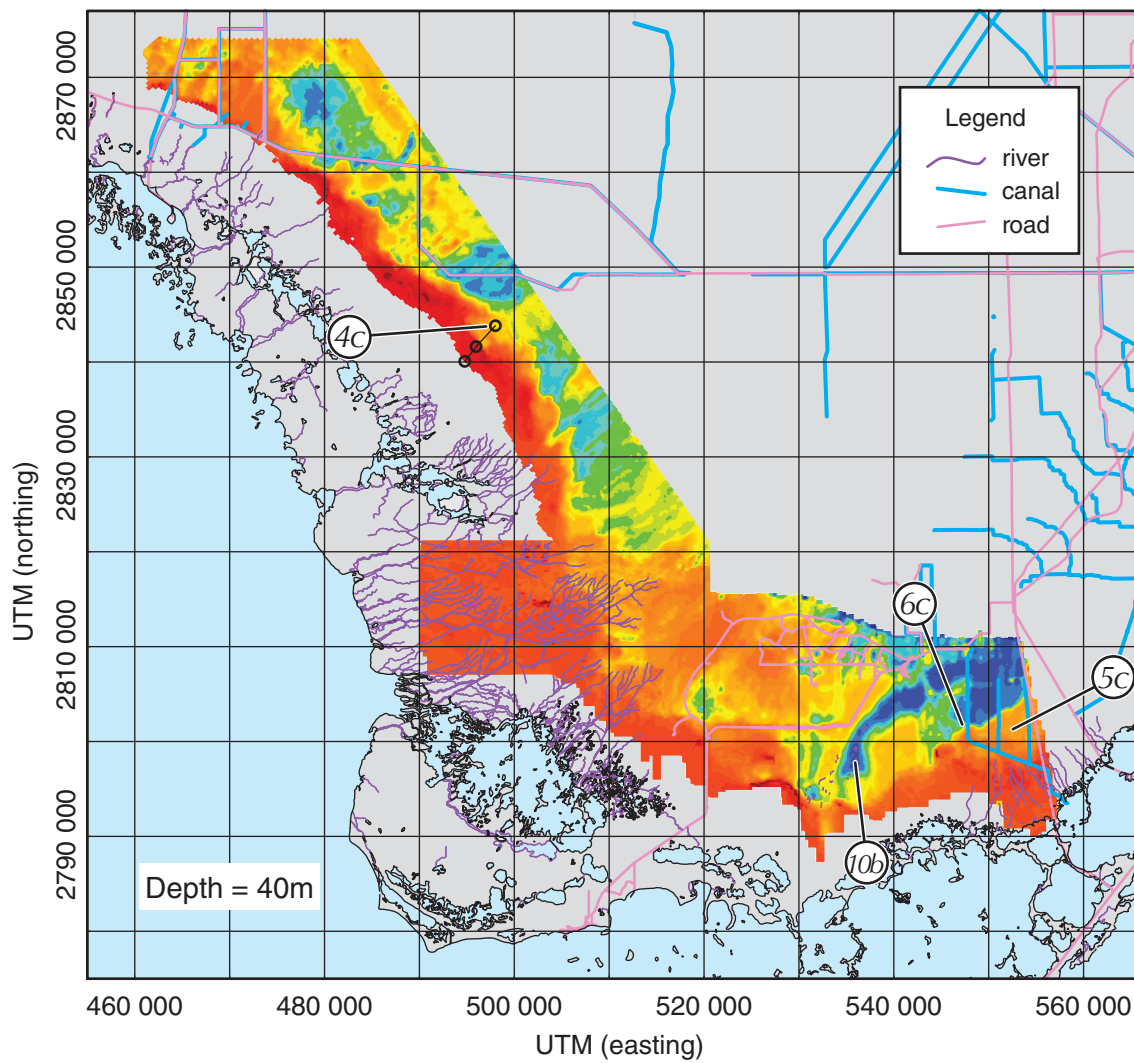
Figure 5 Resistivity depth-slice map at 20 m.

Figure 6 Resistivity depth-slice map at 40 m.

the hydraulic head. The result is that the FWSWT is much further landward in drained than undrained areas.

Variations of the FWSWT with depth can be seen by comparing the various depth-slice maps. In the Big Cypress coastal area the transition moves landward with depth as expected by the Ghyben-Herzberg model. (See the circles associated with Features 4a, 4b, and 4c that locate the transition.) This regular and expected behavior is not seen in all locations. In the eastern portion of the ENP survey (Feature 5) the 20-m depth slice is more conductive (evidenced by the darker orange color) than shallower or deeper depth slices. This behavior was seen in well logs in the area (Fish and Stewart, 1991) and is attributed to a very permeable zone at the base of the Biscayne aquifer where sea water is currently intruded. Below the Biscayne aquifer in the semiconfining unit the formation is more resistive due to lower porosity and relict seawater that has been diluted by mixing with surface water during a time of lower sea level.

Man-made features have influenced the FWSWT in the region. For example, where control structure S-18C blocks canal C-111 (Feature 6), fresh water backs up behind the control structure and infiltrates through the unlined canal walls. As a result the FWSWT is fixed at the control structure, but in the surrounding areas it is further seaward. This results in the cusp in the resistivity maps (Features 6a, 6b, and 6c).

Another interesting low resistivity zone (Feature 7) is seen running westward from the large bend in the old Ingraham Highway. This highway was built between 1915 and 1919 by digging a canal and using the removed material to form the roadway. Near Feature 7 a large cavern was discovered during excavation of the canal. The cavern was about 10 m across and over 10 m deep (Stewart et al., 2002). If the cavern communicated with the semiconfining unit below the Biscayne it could serve as a source of saline water and could produce the low resistivity zone along the canal. Another possible cause would be seawater from Florida Bay that flowed up the Ingraham Canal beyond this location. The canal was filled in 1951 from a point 10 km west of Feature 7 all the way to the coast, thereby stopping the infiltration of saltwater. It is hard to imagine that a saltwater signature associated with the canal still exists more than 50 years later.

Most of the study area is covered with water ranging in depths from 10 cm to 2 m. Roads are usually built on elevated areas that stand 1 to 2 m above the water. As a result, roads alter the flow of surface water and influence the location of recharge areas. This fact is reflected in the resistivity patterns, which often correspond to the location of roads. For example, in Big Cypress National Preserve, the area inside the Loop Road (Feature 8) is about twice as conductive on the 10-m depth slice map as the area outside the loop and to the south and west. This is due to the fact that overland water flow is diverted around this area by the raised roadway and canals. Another example is seen along a north-south section of the main park road (SR 9663) near UTM E 520 000 m, where the interpreted resistivity changes by a factor of four from the east to west side of the road because the roadbed blocks the westward flow of freshwater out of the Taylor Slough region. (This feature is difficult to see with the color scale chosen for this regional data display.)

Canals also affect the location of the FWSWT along the western end of the Tamiami Trail. Here the landward extent of saltwater intrusion is controlled by the canal alongside the road (right side of Feature 9). The canal aligned perpendicular to the coast (left side of Feature 9) brings saltwater further landward in much the same way as tidal rivers.

Geologic control also plays an important role in the patterns seen in the depth-slice maps. In Taylor Slough a resistive zone is seen extending to great depth (Feature 10). A great deal of water is pumped into Taylor Slough resulting in recharge of the aquifer. The location of the slough is probably controlled by channel eroded during a period of low sea level and later filled, possibly with lower porosity material than the surrounding formation making the zone resistive.

Parallel northwest trending linear features (Feature 11) are seen in the 10- and 20-m depth slices. The cause of these is uncertain, however, they strike in the same direction as a nearby rock reef that manifests itself as a slight rise in topography. This coincidence suggests that these linear boundaries are caused by structural features that overprint the hydrologic regime.

Finally, we note an interesting high resistivity zone in the far western portion of the ENP survey (Feature 12). This resistivity anomaly was seen on several flight lines and corresponds to an area where the vegetation is different from surrounding areas. In addition, helicopter-borne topographic measurements (Desmond, 2003) indicate that there is a small increase in elevation (10-30 cm) associated with this anomaly. We interpret the higher resistivity as being caused by a fresh-water lens that accumulates under the topographic rise, much as seen under an oceanic island. Here the surrounding area is not ocean, but water covered marshland. The increased fresh-water thickness displaces more saline water below the topographic rise, thereby raising the formation resistivity.

Estimating Water Quality From HEM Data

As discussed previously formation resistivity and pore water conductivity are related by the formation factor. The formation factor incorporates all effects due to the characteristics of the rock matrix, such as lithology, porosity, pore geometry, and fractures. Chloride content can also be estimated from the geophysical measurements using an experimentally determined relationship between chloride content and specific conductance for surface water samples in south Florida (A. C. Leitz, USGS, written commun., 1998). A chloride scale based on this relationship is plotted on the upper axis of Figure 3. When the aquifer properties are constant, estimating SC and chloride content from the HEM or other geophysical measurements is fairly reliable. In a situation where the geology changes across a region, as is the case for the 80-km by 100-km area under study, there is more uncertainty. We see in Figure 3 that the formation factor varies by a factor of 2 between the western wells in the gray limestone aquifer and the eastern wells in the Biscayne aquifer. This variability poses practical concerns when estimating the chloride content for purposes of hydrologic model development. Clearly the hydrologic modeler must take into account the location and geometry of the various aquifers, being careful to select the appropriate formation factor. The inherent uncertainty is much greater than from actual water samples as indicated by the scatter of the data points seen in Figure 3. The point of this discussion is that the limits of using geophysical data to estimate hydrologic parameters must be weighed against the benefit of the higher sampling density of the data. Furthermore, the uncertainty must be considered when using these data to develop hydrologic models.

Conclusions

This example from south Florida demonstrates the utility of electromagnetic data for mapping saltwater intrusion in a coastal aquifer. Detailed electrical resistivity models of the subsurface are developed through inversion of helicopter electromagnetic data. These models show the features associated with natural saltwater intrusion and the effects of human activity in the Everglades. Time-domain electromagnetic measurements have played a secondary, but important, role in verifying the

HEM interpretation. Borehole induction logs have been critical in developing a relationship between the geophysical resistivity model and ground-water quality, thereby enabling estimates of chloride content to be made from the geophysical results. These estimates are not as reliable as those obtained from actual well sampling, however, they effectively allow the well-sampling data to be reliably extended across the survey area at much greater sampling density, revealing features that would usually not be detected. This increased lateral detail comes at a price of lower vertical resolution compared to well data. However, by combining both types of data the advantages of each can be incorporated allowing estimation of water quality information needed for solute transport, ground-water flow models.

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